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Status of the High-Frequency Benchmark Propagation Analysis Program

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INTRODUCTION

The goal of this work is to develop techniques that permit timely and efficient evaluation of different propagation models in the high-frequency (HF) regime. The resulting program is to be as sophisticated as possible, with concerns for computer run times to be subordinate to the use of realistic models of the environment. The program will be used with new databases of high-latitude propagation measurements to evaluate and improve the faster running models and point to deficiencies in the ionospheric and propagation models. In conjunction with this development, new displays will enhance understanding of the propagation environment. For portability and ease of access, the program will run on personal computers. The current operating system is OS/2, and we are using the WATCOM compiler.

SPATIAL INTERPOLATION

The key to using arbitrary models of the ionosphere in the HF Benchmark is the development of a generalized spatial interpolation algorithm that will accept these models and allow accurate ray tracing through a geographically defined grid. Ferguson and Shellman (1993) described a technique for this spatial interpolation based on uniformly spaced data in all three spatial dimensions. This technique is designed for a geographical grid of ionospheric profiles defined by a propagation path between a specified transmitter and receiver. Ionospheric profiles are calculated along the path and at locations normal to the path at distances of 200 and 400 km from the path so as to create a uniform horizontal spacing of profiles. Uniformity in the vertical direction is achieved by interpolating the electron density values received from the ionospheric model at irregular intervals of height onto a set of altitudes at evenly spaced intervals. The result is a fast algorithm with continuous values of the electron density and its spatial derivatives.

The ionospheric model produces electron densities at heights close together (10 km) in the lower part of the ionosphere and farther apart (50 km and 100 km) at F-region heights. This gives better definition of features such as sporadic-E in the lower ionosphere. We now recognize that the efficiency of interpolation using a uniform spacing of altitudes is not as important as accommodating the actual output from the model. So we have modified the spatial interpolation to allow for nonuniform spacing of the electron densities in all three dimensions. However, we still calculate vertical profiles of the electron density in a uniform horizontal grid. The procedure for generating the coefficients of interpolation is the same as described in Ferguson and Shellman (1993) with inclusion of the spacing parameters.

IONOSPHERIC MODEL

The ionospheric model has been upgraded to the Parameterized Ionospheric Model (PIM), Version 1.0.7 (PIM is available from Computational Physics, Inc., 240 Bear Hill Rd., Suite 202A, Waltham, MA 02154). A subroutine named *Get_Profile* has been developed to obtain ionospheric profiles from the subroutines of the PIM, where the solar and geophysical parameters are supplied by the calling routine. Previous implementations of this model involved removing a number of routines from the PIM library because they are replaced by our input routines and *Get_Profile*. Other changes were made to comply with the requirements of the WATCOM compiler. The most significant modifications are noted below.

Originally, subroutines *LRDEOFF, LRDOPCF, OPEN_FILE, RDCGDB, RDEOFF, RDOPCF,* and *READAWS* created file names by concatenating strings in the argument list of a called subroutine.

Our compiler does not allow concatenation of strings in an argument list, so we do the concatenation before calling the required subroutine. Subroutine *OPEN_FL* originally opened scratch files with names. Our compiler does not allow named scratch files, so we simply deleted the name field from the *OPEN* statements. Originally, subroutine *GLOBE5* had an array named *P* dimensioned for 139 values. However, the calling routine has this same quantity dimensioned for 150 values, so we changed the dimension in this subroutine to match that in the calling routine. Subroutine *OUTPUT* originally opened the output file with *STATUS = "NEW"* which, under the original development platform running *VMS*, opens a new version of the file if the name is the same from one run to the next. Under *DOS* and *OS/2*, this causes an error if the file already exists, so we changed the status to *"UNKNOWN."* Subroutine *REGMOD* generates the output data for the program. We want electron density profiles and *foF2*, *hmF2*, *foE*, and *hmE*. To get this output, the original version of this subroutine required two calls (with the attendant duplication of calculations). We increased the dimension of the array *CDATA* by four to allow retrieval of the extra parameters with just one call to the subroutine. Finally, we renamed the string routine *LENGTH* to *LENGTHS* because one of our resident libraries already uses the first name.

One of the primary uses of the real-time version of the PIM is in space forecasting. In this application, users routinely generate a global grid of ionospheric electron density profiles by using a variety of real-time inputs. Thus, it is important for us to be able to use this global grid directly with the ray-tracing routine. Obviously, that is one of the reasons why we implemented the nonuniform spacing of profiles in the spatial interpolation routine. A difficult problem remains in handling paths that cross the polar regions since the rectangular formulation breaks down there.

RAY TRACING

Minor changes have been made to the ray-tracing routines. The printout has been corrected to properly display the results for absorption calculations. However, without a D-region in the ionospheric model, this calculation only gives us the deviative absorption.

SAMPLE PROBLEM

A sample problem is presented here to illustrate the unification of the individual models. The path is from Forsyth, Montana, to San Diego, defined in geographic coordinates from 46.4°N, 107.0°W to 32.7°N, 117.2°W. The computed geographic bearing angle from the transmitter to the receiver is 213.3°, and the length of the path is 1770 km. This path is being used for an experiment to measure field strength at three frequencies: 3.35, 7.8, and 14.4 MHz.

For the ray-tracing runs, rays were launched at an azimuth of 213° and at elevation angles from 0° to 90° in steps of 2°. The ionospheric profiles were generated for 15 April at 0800 UT (night) and 2000 UT (day). Two different cases of solar activity were used, one quiet ($k_p = 2$) and the other disturbed ($k_p = 6$). In the quiet case, the 10-cm flux was 78.7 erg/cm^2/s, the k_p was 2, and the direction of the sun's magnetic field, B_y, was positive. Using the built-in conversion from solar flux to sunspot number, we get 20 for the sunspot number. In the second case, all of the parameters are the same, except that k_p was set to 6.
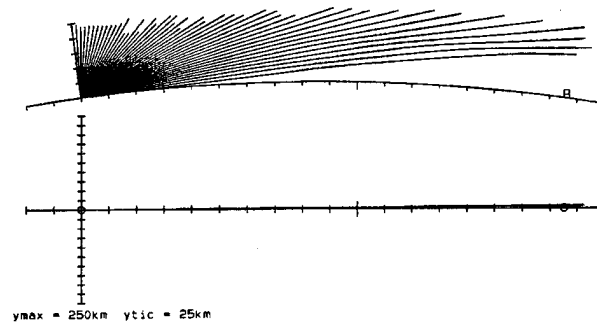
Ray paths for ordinary rays at each of the frequencies under quiet conditions at night are shown in the first three panels (a, b, c) of figure 1. Each panel shows the projection of the ray paths onto the vertical plane passing through the transmitter and the receiver (top portion of panel) and onto the
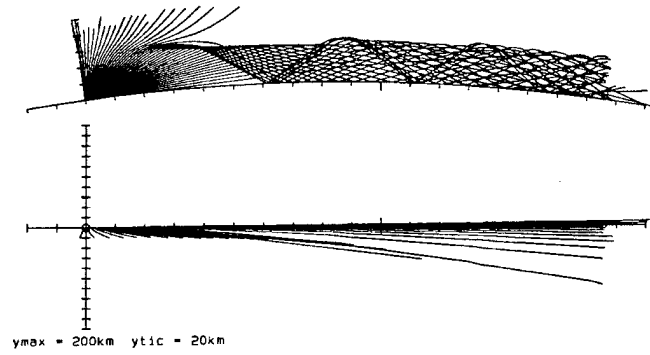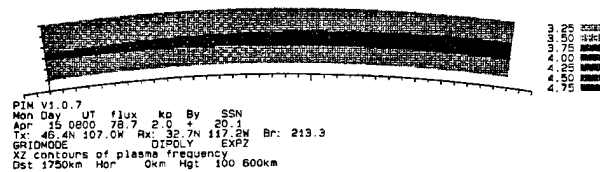
(a) 3.3 MHz
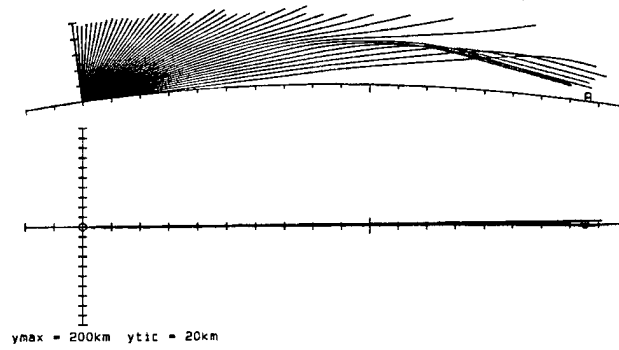
(b) 7.8 MHz

(c) 14.4 MHz

(d) electron density contours

Figure 1. Ray paths and electron density contours for Montana to San Diego; 0800 UT (Night); $k_p = 2$.

ground (lower portion of panel). In the latter projection, locations above the horizontal axis are east of the propagation path because it is in a north to south direction. The last panel (d) of the figure shows contours of electron density in the vertical plane along the propagation path. The ionospheric model gives a broad maximum between 200 and 500 km, the width varying slightly from one end of the path to the other. Most of the rays at 14.4 MHz penetrate the ionosphere. A single hop is possible at 7.8 MHz, with reflection taking place near the middle of the path. Multiple modes occur at 3.3 MHz.

The results for disturbed conditions are shown in figure 2. There is an enhancement of ionization, especially at higher latitudes. Furthermore, the ionization is not uniform along the path. The modes at each frequency do not change very much, but there is a marked increase in deflection of the rays out of the path between the transmitter and receiver.
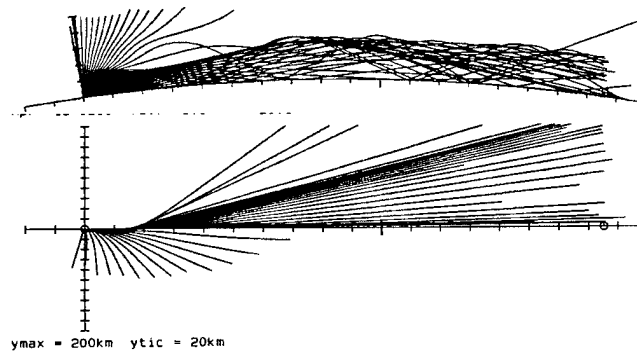
Results for daytime conditions are shown in figures 3 and 4. The contour plots of electron density show little discernible difference between quiet and disturbed conditions, with corresponding small differences in the ray paths. However, there are some strange paths taken by the rays at 3.3 MHz, especially for the disturbed conditions. We have not yet determined the cause of these results.
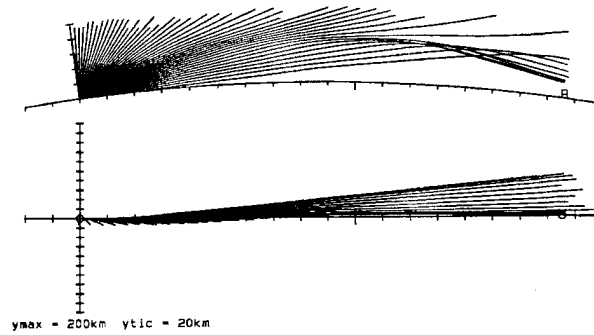
IONOSPHERIC DISPLAYS

The ionospheric displays developed by Ferguson (1993) were modified to use filled contours instead of contour lines. The algorithms developed by Ferguson and Shellman (1993) to produce the filled contours were somewhat crude in that they essentially produced a series of filled rectangles along specified curves. This year we searched the literature for better algorithms and found none that met our requirements. So we developed our own routines. These new routines follow pairs of contour lines that define the filled contour area. They search for voids within each contour area and create a series of connected polygons to produce a single filled polygon. The new routines produce smoother contour plots and can write to any device that supports the Hewlett-Packard Graphical Language (HPGL), including LaserJet IIIs and 4s.
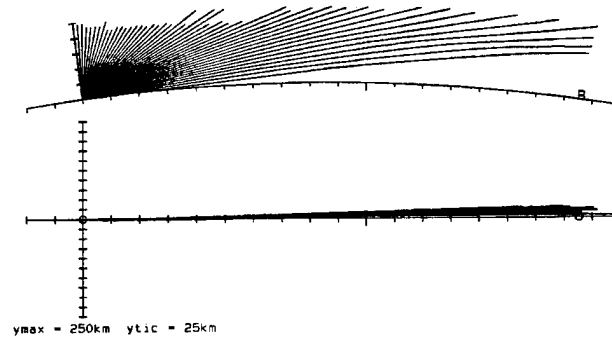
FUTURE PLANS

As described above, we plan to modify the ray-tracing routine to accept the global grid generated by the PIM program. This means that we will make separate runs to generate the ionospheric data and to do the ray tracing. Furthermore, we will have to handle the poles properly to get the correct continuity of the electron densities and their derivatives. We also plan to begin running the model to compare its output with data on paths that are part of a database used to develop HF propagation models.
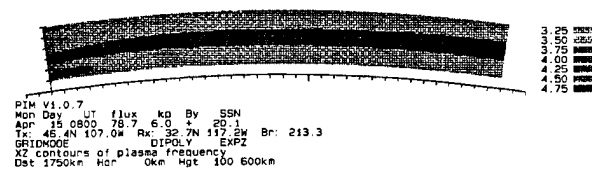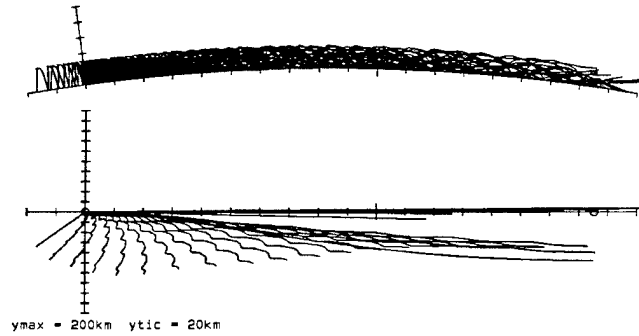
ymax = 200km   ytic = 20km

(a) 3.3 MHz

ymax = 200km   ytic = 20km

(b) 7.8 MHz

ymax = 250km   ytic = 25km

(c) 14.4 MHz

3.25
3.50
3.75
4.00
4.25
4.50
4.75

PIM V1.0.7
Mon Day   UT flux   kp By   SSN
Apr 15 0800 78.7 6.0   +   20.1
Tx: 46.4N 107.0W Rx: 32.7N 117.2W   Br: 213.3
GRIDMODE   DIPOLY   EXPZ
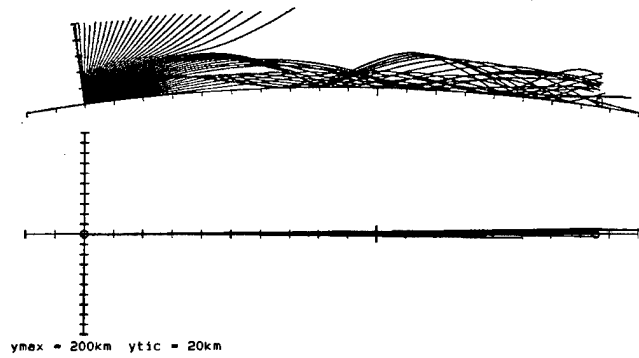XZ contours of plasma frequency
Dst 1750km Hor   0km Hgt 100 600km

(d) electron density contours

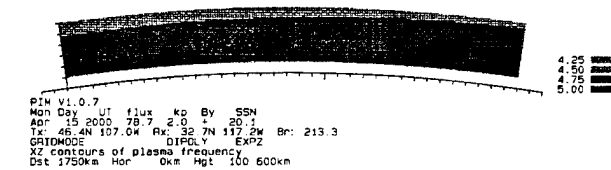**Figure 2**. Ray paths and electron density contours for Montana to San Diego; 0800 UT (Night); $k_p = 6$.

5

ymax = 200km   ytic = 20km

(a) 3.3 MHz

ymax = 200km   ytic = 20km

(b) 7.8 MHz

ymax = 250km   ytic = 25km

(c) 14.4 MHz

PIM V1.0.7
Mon Day   UT flux   kp By   SSN
Apr 15 2000 78.7 2.0 + 20.1
Tx: 46.4N 107.0W Rx: 32.7N 117.2W Br: 213.3
GRIDMODE   DIPOLY   EXPZ
XZ contours of plasma frequency
Dst 1750km Hor   0km Hgt 100 600km

4.25
4.50
4.75
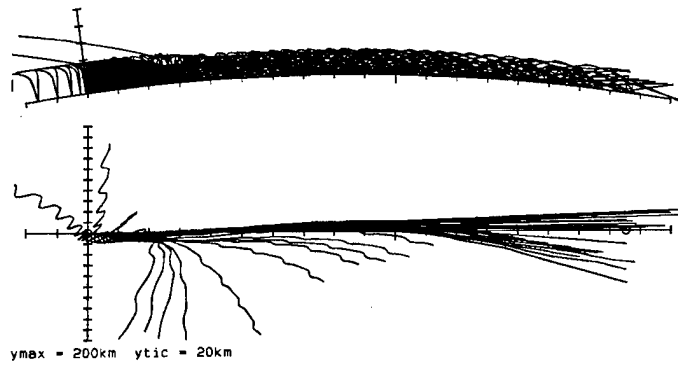5.00
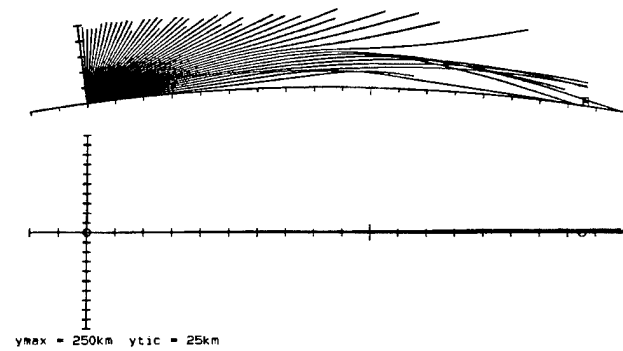
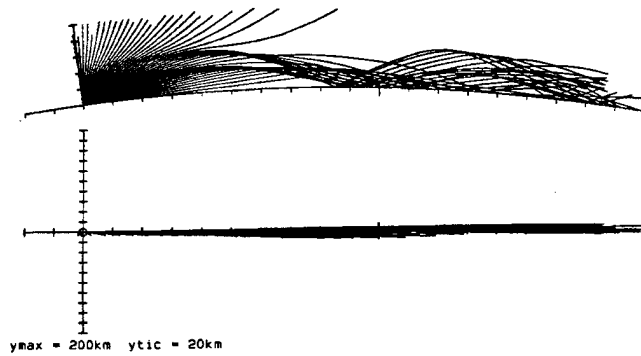(d) electron density contours

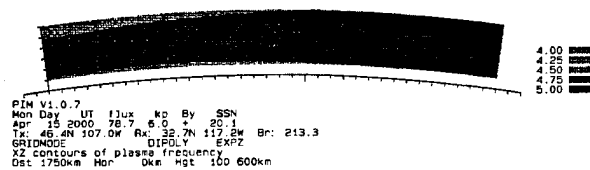**Figure 3**. Ray paths and electron density contours for Montana to San Diego; 2000 UT (Day); k_p = 2.

6

ymax = 200km   ytic = 20km

(a) 3.3 MHz

ymax = 200km   ytic = 20km

(b) 7.8 MHz

ymax = 250km   ytic = 25km

(c) 14.4 MHz


```
PIM V1.0.7
Mon Day   UT  fJux   kp  By   SSN
Apr  15 2000  78.7  6.0  +   20.1
Tx: 46.4N 107.0W  Rx: 32.7N 117.2W  Br: 213.3
GRIDNODE              DIPOLY    EXPZ
XZ contours of plasma frequency
Dst 1750km  Hor   0km  Hgt 100 600km
```
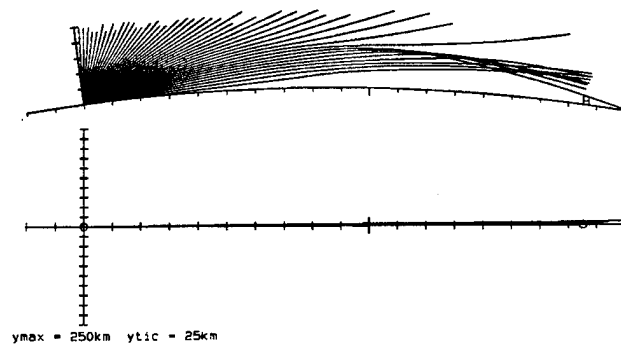
(d) electron density contours

Figure 4. Ray paths and electron density contours for Montana to San Diego; 2000 UT (Day);
$k_p = 6$.

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Ferguson, J. A., and C. H. Shellman. 1993. "The High-Frequency Benchmark Propagation Program," NRaD TD 2608 (Oct). Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA.

Jones, R. M., and J. J. Stephenson. 1975. "A Versatile Three-Dimensional Ray Tracing Computer Program for Radio Waves in the Ionosphere," U. S. Dept. of Commerce Office of Telecommunications Report 75-76 (Oct).

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13. ABSTRACT *(Maximum 200 words)*

The High-Frequency Benchmark Propagation Analysis Program is a computer code that will permit timely and efficient evaluation of different propagation models in the high-frequency (HF) regime. This report documents improvements to the program made during 1994.

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